Journal of the Royal Society of Western Australia, 82:33-49, 1999

Bornhardt inselbergs in the Salt River Valley, south of Kellerberrin, Western Australia (with notes on a tesselated pavement in granite and pinnacles in laterite)

C R Twidale[1], J A Bourne[1] & J R Vidal Romani[2]

[1] Department of Geology and Geophysics, University of Adelaide, Adelaide SA 5005
email: *rtwidale@tellus.geology.adelaide.edu.au*
[2] Facultad de Ciencias, Universidad de Coruña, Campus de Zapateira, 15071 A Coruña, Galicia, Spain
email: *xeoloxia@udc.es*

(Manuscript received June 1998; accepted January 1999)

Abstract

Several prominent bornhardts, or dome-shaped granitic hills, occur in or near the valley of the Salt River, south of Kellerberrin, Western Australia. They originated as subsurface bedrock rises projecting into the base of a regolith produced by fracture-controlled weathering beneath a lateritised land surface in Cretaceous and earlier Mesozoic times. They were exposed during the Early Cainozoic by the stripping of the regolith by a rejuvenated Salt River and its tributaries. By the Miocene, the river had cut a bedrock gorge below the present valley, but this has since been infilled and buried. Some effects of weathering by and in the lateritic carapace are noted.

Introduction

The Salt River is part of a complex system of palaeochannels known as the Yilgarn River catchment (Salama 1997), which drains to the Indian Ocean via the Swan River and which occupies an area of about 130000 km^2 in the south-western part of the Archaean Yilgarn Craton of Western Australia. Although it usually comprises a few narrow channels and with every appearance of being sluggish, in flood the river occupies a wide channel. The present broad flood plain, with several narrow individual channels could be the trace of an old meander belt, but if the channel indicates the former extent of the river then its geometry suggests a high (flood?) discharge, possibly related to a Miocene or Pliocene period of higher rainfall (*e.g.* Kemp 1978; see also Salama 1997). South of Kellerberrin the river flows from east to west, and its valley is incised some 100 to 120 m below the level of the high plain surface of the interfluves to the north and south.

Several prominent granite hills occur in and adjacent to the Salt River Valley. With two exceptions, they are basically domical in form, although the geometry of the domes varies from elongate, as with Mt Stirling, Tutakin and Gundaring hills, to dome-on-dome (or "cottage loaf") at Kokerbin Hill, to a simple hemisphere at Middle Dome, between Mt Stirling and Gundaring. Known in different parts of the world as demi-oranges, meias laranjas, dwalas, morros, matopos, and ruwares, they are here referred to as bornhardts, after the German scientific explorer of that name (Bornhardt 1900; see also Willis 1934; Twidale 1982a; Campbell 1997). The exceptions are Nangeen Hill, which is a block- and boulder-strewn nubbin or knoll, and a small residual between Mt Stirling and Tutakin Hill which similarly consists of a scatter of blocks and boulders, on a low rise. Whatever their morphology, they stand in isolation, so that all these residuals are also inselbergs or "island mountains".

A block is an angular rock mass, usually cubic, quadrangular or rhomboidal, but a boulder is more-or-less rounded and at least 25 cm diameter. Boulders differ from what have informally been called haystacks or pillars (*e.g.* Twidale & Campbell 1984) in that the latter remain in physical continuity with the underlying rock mass, whereas boulders are detached. In the Salt River Valley the major divides are broad and rolling. Large areas are covered by what appears to be a thin regolith separating extensive rock platforms or low large-radius domes, many of them with a scatter of blocks and boulders. Such assemblages are natural. There is no suggestion that they were constructed or reorganised by humans for interment or, indeed, any other purpose. There is, therefore, no justification for calling them tumuli (Main 1997 p115), for a tumulus (or barrow) is a stone-lined burial chamber covered by debris and looking like a low, smooth, rounded, frequently elongate hill.

The term "tor" has been applied to both boulders and bornhardts (*e.g.* Williams 1936; Hills 1940 pp26-28; Cotton 1948 p30; Mabbutt 1952; Thomas 1965; Main 1997) but, increasingly, it is recognised that "tor" is a regional British term applied to steep-sided angular or castellated hills ("about the size of a house"; Linton 1952, p354). It is not apposite to any of the forms discussed in this paper, most of which are bornhardts; which are moreover the basic forms from which both nubbins and castle koppies evolve (Twidale 1981). The origin of such domical hills has long been the subject of vigorous debate (for reviews, see Twidale 1982a,b; Vidal Romani & Twidale 1998). The residuals discussed here take on a special significance because they occur in a setting that allows their evolution to be reconstructed and their age to be determined. This study is dedicated to an analysis of the origin of these forms, though the origin of several other features is also broached.

Figure 1. Geology and palaeodrainage in south-western Western Australia (modified from Anon 1975; Commander 1989).

Geological and Topographical Context

The Yilgarn Craton (Fig 1) is one of the Western Cratons of Australia (Palfreyman 1984). In the south, in the area known as the Wheatbelt, Archaean gneiss and granite dating from about 2.64 Ga (Myers 1993; Nemchin *et al.* 1994) are dominant, though there are minor but economically important NNW-SSE trending bands of "greenstone" which consist predominantly of metamorphosed basalt, dolerite and other basic rocks (Fig 1). The area is traversed by prominent NW-SE fracture zones (lineaments) of latest Archaean or earliest Proterozoic age, with ENE-WSW and latitudinal trends also well represented. All have influenced stream development and hence stream patterns (Fig 2). Both in Zimbabwe and in Western Australia, such granitic bodies are conventionally regarded as being diapirically emplaced into flat-lying greenstone sequences (MacGregor 1951; Anhaeusser 1984; Hickman 1984) but Myers & Watkins (1985) attribute the outcrop patterns of the Yilgarn to the simultaneous deformation of greenstone and granites in large-scale fold interference dome-and-basin structures.

The Salt River area is dominated by outcrops of a medium and coarse-grained, in places porphyritic, adamellite (Muhling & Thom 1979; Chin 1986). The high plains to either side of the Salt River Valley are underlain by laterite, the lower by alluvium, with granite exposed, typically in large radius bornhardts, on the slopes

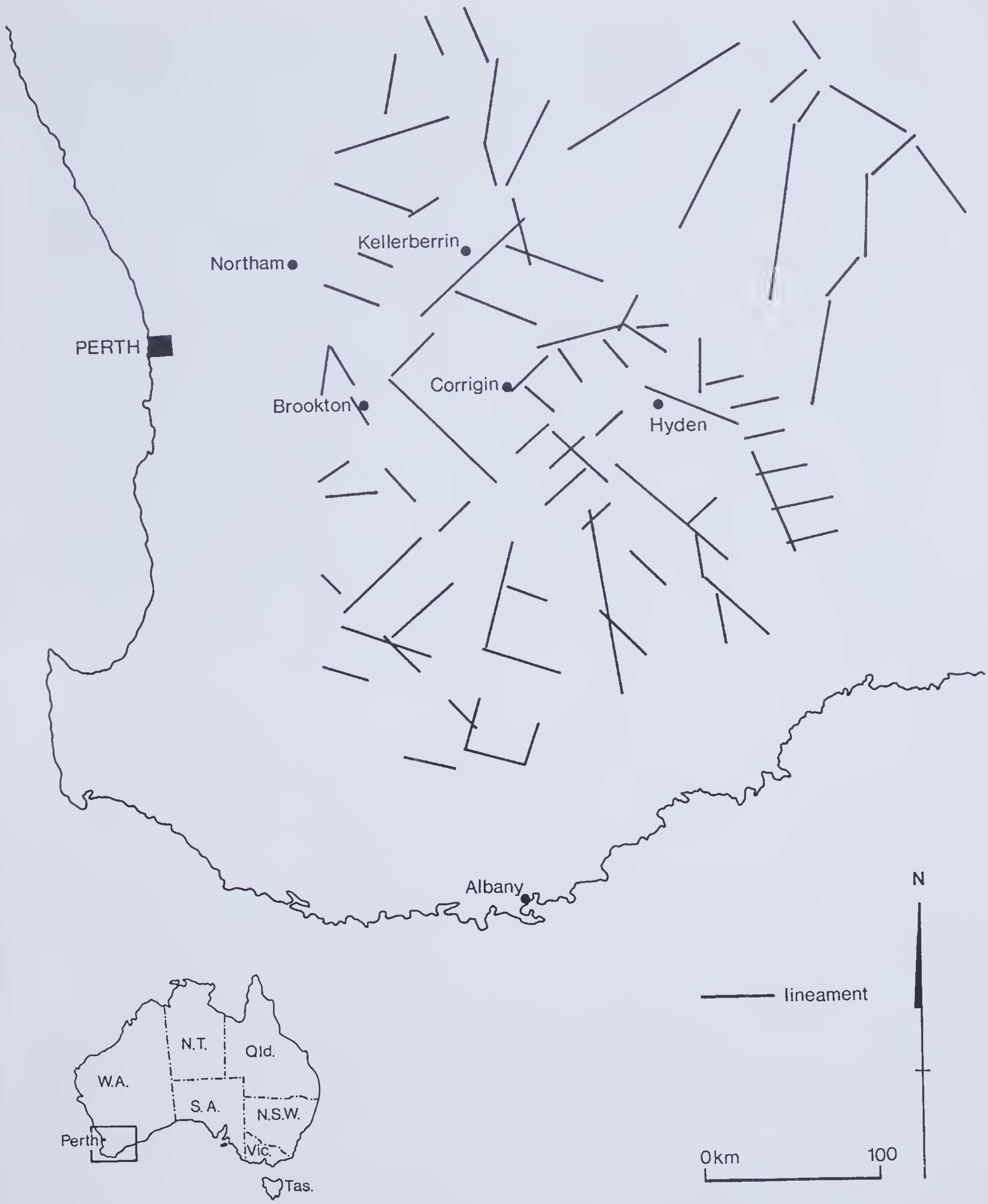

Figure 2. Inferred fractures (lineaments) in the southern Yilgarn Craton. Many are exploited by rivers (*cf* Fig 1).

between the two (Fig 3). Mt Stirling, Mt Caroline, Gundaring Hill, Tutakin Hill, Nangeen Hill and Kokerbin Hill are especially prominent domes exposed within or close to the channel of the Salt River.

The weathered mantle which underlies the high plains is well exposed at the low mesa informally referred to as Repeater Hill, where a thin (5 m) profile of primary laterite is exposed in a shallow quarry and in natural bluffs (Fig 4). It consists of a thin (up to 5 cm) sandy A-horizon overlying a pisolitic ferruginous zone about a metre thick, and underlain by about 4 m of kaolinised granite which grades down into weathered bedrock. The pisolitic zone is exposed in a bluff in which are scored cyclindrical tubes or pipes up to 15 cm diameter. That

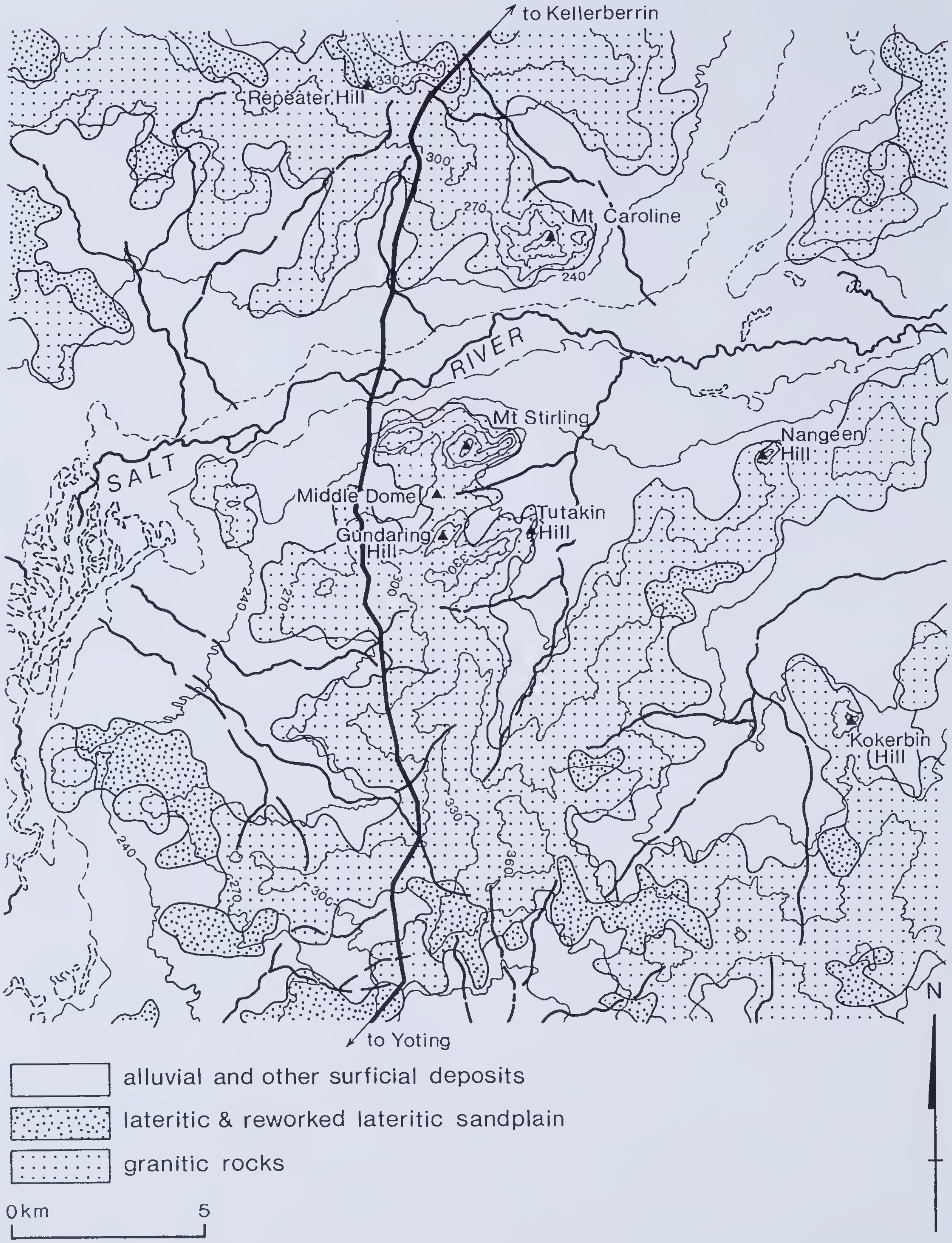

Figure 3. Major geological and topographical features of the Salt River Valley and environs (modified from Series R712 Sheet 2435-III *Pantapin*. Edition 1 - LSWA; Geological Series Sheet SH 50-15 *Kellerberrin*. Geological Survey of Western Australia).

Figure 4. Laterite exposed at Repeater Hill. P: pisolitic zone, overlying kaolinised rock in scarp, and weathered granite at scarp foot.

much of the ferruginous zone is penetrated by such pipes is suggested by the presence of hollows filled with sand and pisolitic detritus on the surface of the mesa.

Morphology of the Bornhardts

All of the Salt River Valley bornhardts display well-developed sheet structures, or thick slabs defined by parallel arcuate fractures. Many of them, as at Kokerbin Hill, and Gundaring-Tutakin, are so steeply dipping that there has been failure and slippage (Fig 5). Large residual blocks and boulders (some of them perched or balanced), rock basins and Rillen (gutters and flutings), fracture-controlled clefts (also known as Kluftkarren, and slots in the USA), largely enclosed hollows or tafoni developed on boulders and under sheets (some of the latter with collapsed roofs), cliff-foot caves, and flared slopes are also well and widely represented (Fig 6). A-tents, or pop-ups, (Fig 7A) and displaced slabs are also developed. Numerous minor fault displacements have been noted. Siliceous speleothems (Fig 7B) are abundantly developed at several sites (Vidal Romani *et al.* 1998).

- Mt Caroline is a bevelled bornhardt. The crest, averaging 310 m asl (above sea level), is boulder-strewn and at 340 m asl its blocky summit stands some 90-100 m higher than the adjacent plain. A minor boulder-strewn secondary peak (310 m) surmounts the eastern section of the hill (Fig 8).
- Mt Stirling comprises two offset elongate complex domes trending NE-SW (Figs 3 & 9) and connected by a slightly lower granite ridge. The base of the hill stands at 250-290 m asl, the crest of the west dome at 330 m plus, and the east dome at 370 m plus asl. A rock platform on the southern flank of the western dome stands at 290 to 300 m asl. The plan outlines of the residual are determined by steeply-dipping NE-SW fractures, within which sheet fractures and structures (Fig 5A) are developed. A-tents indicate expansion of up to 10% on compression and rupture. Flared basal slopes on the southern base of the eastern dome are associated with steeply dipping sheets and appear to have developed beneath talus accumulations. One sector of this slope appears to have been protected against basal sapping and weathering by stream diversion along fractures (Fig 10). Tafoni, rock basins and shallow gutters are widely developed and speleothems occur at suitable sites.
- Middle Dome is located between Mt Stirling and Gundaring Hill (Figs 3 & 9). As its name suggests it is a hemisphere or half-orange, smooth, devoid of soil and vegetation, and standing at about 300 m asl and 20 m above the level of the surrounding plain.
- Gundaring Hill and Tutakin Hill consist of two offset elongate (NE-SW) domes linked by a col (Fig 9). Tutakin Hill stands 300 to 360 m plus asl, and Gundaring Hill 270 to 370m asl plus and some 90 to 100 m higher than the adjacent plains and valleys. Kluftkarren, rock basins, A-tents, steeply dipping sheets and slipped slabs are represented as are large boulder tafoni with speleothems.

A

B

Figure 5. A: Sheet structures exposed in Mt Stirling. B: Slipped slab at Kokerbin Hill.

- Nangeen Hill is a boulder-strewn nubbin standing 270 to 310 m plus asl, and 40 m above adjacent plain.
- Kokerbin Hill (Fig 11) is a dome-on-dome structure with a shoulder at about 320 m asl and the crest at 360 m plus. The summit stands some 70 m higher than the surrounding plains. A minor boulder-strewn hill NNW of the main peak rises to more than 320 m plus. Basal flares and associated tafoni are prominent as are steeply dipping and slipped sheet structures (Fig 5A). Splitting and displacement of crystals along sheet structures indicates dislocation along sheet partings (Fig 12). Boulder tafoni, speleothems, A-tents (on lower slopes), tafoni with collapsed roofs (Fig 6), and chaotic masses of disturbed blocks and slabs also occur.

Origin of the Bornhardts

Why are bornhardts in general, and in particular those of the Salt River Valley, upstanding? Several hypotheses have been advanced in explanation of the residuals (for reviews, see Twidale 1982a,b; Vidal Romani & Twidale 1998). Many hypotheses have local validity, but the two proposed as general theories and most commonly cited involve scarp retreat and structural factors, and particularly fracture density.

According to the scarp retreat hypothesis (Fig 13A), bornhardts and other inselbergs are the last remnants remaining after long distance scarp retreat (Holmes 1918; King 1942, 1949; see also Ollier & Tuddenham 1962; Selby 1977). They ought therefore to be located on major divides and not in or near major river valleys. However, all but one of the most prominent residuals of the Salt River area occur close to the main channel and within the dissected fringe of the adjacent plains. Even Kokerbin Hill, which is some 6 km from the Salt River channel, although still within the zone of dissection, at its base stands only 70 m above river level.

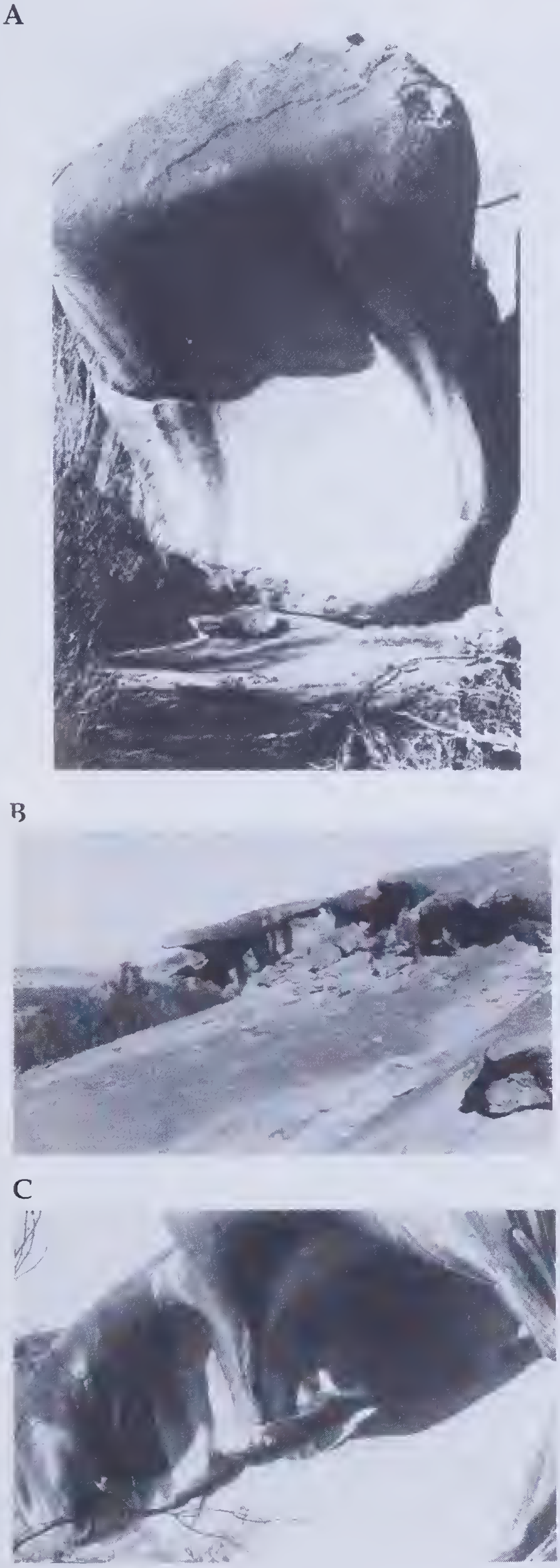

Figure 6. Kokerbin Hill: **A:** boulder tafone, **B:** tafone with collapsed roof, **C:** cliff-foot cave and flare.

The second widely accepted explanation of bornhardts is that they are structural forms developed on compartments of rock which are more resistant than the surrounding rock masses, and which withstand subsurface moisture attack (Fig 13B). The greater resistance of compartments may reflect either rock composition or fracture density (massive, low density or widely spaced partings). When base-level is lowered the weathered zones are evacuated and the bedrock surface - the erstwhile weathering front (Mabbutt 1961) - is exposed, with the resistant compartments upstanding. This two stage explanation was first advocated by Falconer (1911) and has since found widespread support both in the field and in the comparatively recent literature (*e.g.* Linton 1955; Wilhelmy 1958; Ollier 1960; Twidale 1964, 1982a; Thomas 1966; Godard 1977). Variations in structure most commonly take the form of contrasts in fracture density. These may be due either to folding producing antiforms and synforms, domes and basins (*e.g.* Lamego 1938; Myers & Watkins 1985), or shearing (Twidale 1980), in each instance leading to the development of compressive cores which develop into bornhardts.

Local evidence suggests that the Salt River Valley bornhardts have developed in this way. The regional pattern of palaeochannels is determined by gross fracture patterns (Salama 1997) dominated by NE-SW trends, although with prominent ENE-WSW and east-west elements (Figs 1 & 2). The Salt River valley sector south of Kellerberrin is aligned latitudinally and is, and viewed *in toto*, part of the regional pattern. Several of these bornhardts are largely defined by steeply dipping fractures amongst which NE-SW trends are prominent.

The Salt River Valley bornhardts are not the only massive compartments in the area. Low large-radius domes and platforms (most of them unnamed but some of them prominent and impressive) with bare granite exposed are found on the divides. Many are well exposed in the gently sloping sidewalls of the main valley as well as in shallow incised valleys eating back into the watersheds between the Salt and the Mortlock river systems, and in the main channel of the Salt River and various of its left bank tributaries (Fig 1). Their geometry and location suggest that several of these are at least as extensive and massive as Mt Stirling and the other Valley bornhardts, but whereas the latter have been exposed, or partly exposed, as a result of the incision of the Salt River, the others remain essentially concealed by the regolithic cover. Mt Stirling and the other bornhardts of the Salt River Valley are bornhardts because they happen to be located close to the major drainage line of the area.

In reality, the "two-stage" explanation is an over-simplication, for though weathering and erosion are the two prominent stages involved, both processes have exploited older, and in the Yilgarn Craton, much older, structural weaknesses such as fractures in the country rock. The mechanism is really multi-stage for the development of the regional fracture pattern, probably in earliest Proterozoic times, must be taken into account (Twidale & Vidal Romani 1994), but for the sake of brevity the term "two-stage" is retained here.

In the Salt River Valley the residuals are all developed in an Archaean seriate adamellite, which bedrock

A

B

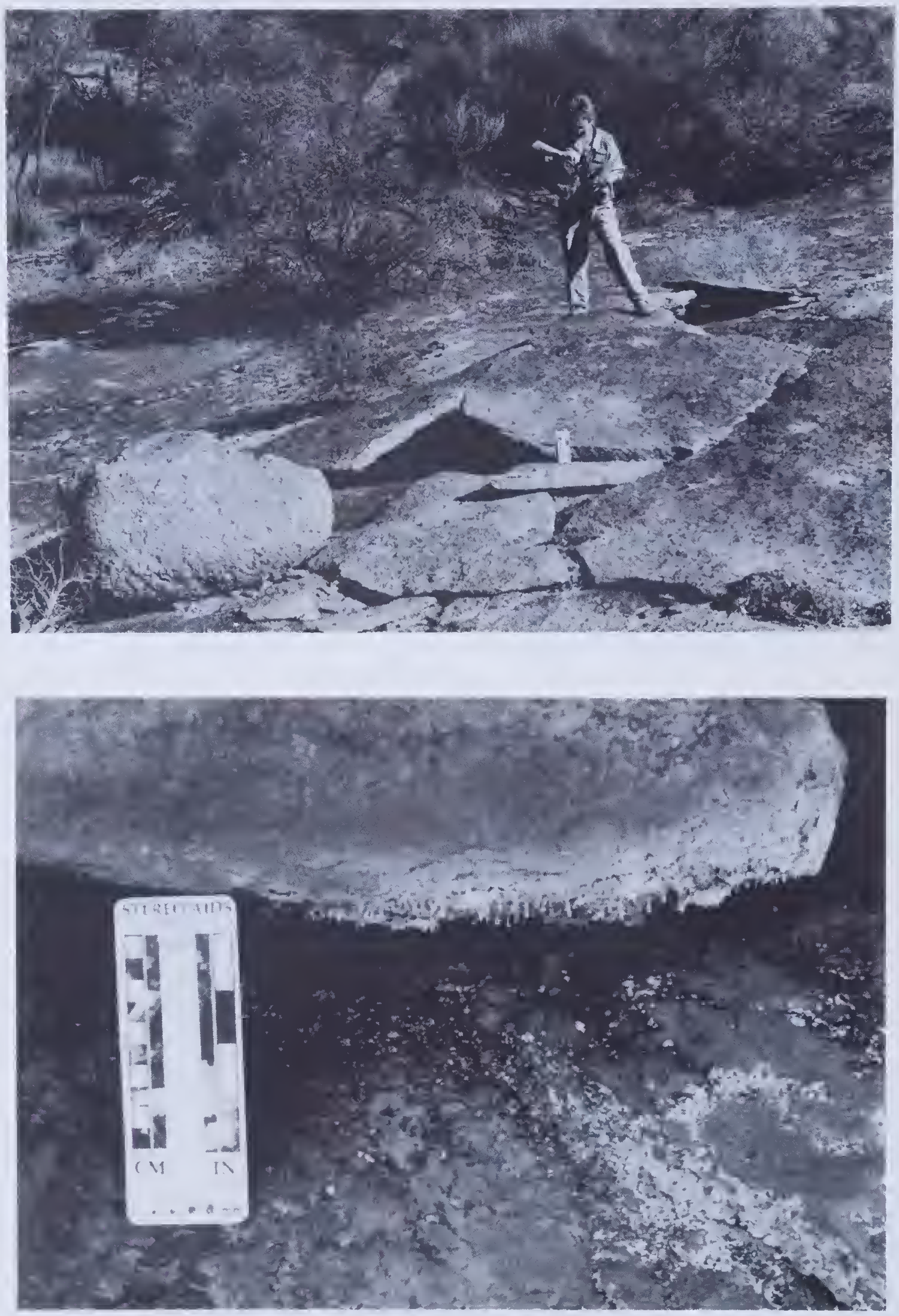

Figure 7. A: A-tent at Kokerbin Hill. B: Siliceous speleothems (stalactites). Each stem is of opal-A, with a tip of gypsum.

Figure 8. The eastern peak of Mt Caroline, showing boulder- and block-strewn crest.

appears both in hill crests and in lower slopes. Variations in fracture density are suggested by the massiveness (scarcity of open fractures in the residuals) compared with the close jointing and mildly weathered granite exposed in some road cuttings and borrow pits at lower elevations in tributary valleys. According to some interpretations sheet fractures on the one hand (Twidale 1964; Vidal Romani *et al.* 1995) and A-tents on the other (Twidale & Sved 1978; Wallach *et al.* 1993) can both be taken as indicating past or continued shearing. The en echelon pattern of Mt Stirling and Gundaring-Tutakin hills is also suggestive, as are the offsets discernible in the distribution of fractures implied by straight channel sectors (Salama 1997; Figs 2 & 9).

Age of the Landforms

General Remarks

In describing the age of a land surface or a landform, geomorphologists use the same convention as geologists and winemakers. Just as a basalt flow which was extruded some 60 Ma in the Eocene and which persists in the landscape is referred to according to its age of initiation, and just as a wine is referred to in terms of the year in which the grapes from which it is derived were harvested, so the age of a landform refers to the date of initiation. In reality, of course, few landforms develop instantaneously; a fault scarp, for example, may, but most landforms evolve over time, so that they have an age-range. However, this characteristic is accommodated in the immensity of time. Just as the basalt earlier referred to is altered in time and the wine matures (or deteriorates), so also do landforms not go unchanged; but all are still labelled according to date of initiation.

Ayers Rock (Uluru), for example, is a domical hill or bornhardt with a prominent bevelled crest, eroded in steeply dipping Cambrian sandstone which stands in isolation in the desert landscapes of central Australia. The summit bevel is an etch surface for it is devoid of soil or regolith. Local stratigraphy suggests it was formed as part of a weathering front in the latest Cretaceous (about 70 Ma) and that it was exposed during the Early Cainozoic, for Oligocene lake beds occur on the plains around the residual. The steep slopes that flank the bevelled summit are much younger, and are due to successive (at least two) phases of scarp-foot weathering and erosion during the Cainozoic.

Salt River Valley

In the Salt River landscape, too, the bornhardts are two-stage forms. They originated as bedrock projections on the weathering front beneath a lateritised land surface during the Cretaceous (and possibly also in earlier Mesozoic times), but were first exposed as domical landforms during the Cainozoic. They may be as old as the Eocene but were definitely exposed by the Miocene, when the Salt River had eroded a considerably deep valley in the adjacent valley floor. The exposure may have been gradual, but it more likely occurred in stages or phases - there are suggestive benches at 290 to 300 m asl and 30 to 40 m above plain level on Mt Stirling (*cf* Twidale & Bourne 1975) - with pauses during which there was scarp-foot weathering.

Figure 9. Extract of vertical air photograph of part of Salt River Valley south of Kellerberrin, showing granitic residuals (1: Mt Stirling, 2: Middle Dome, 3: minor nubbin, 4: Gundaring Hill, 5: Tutakin Hill) and in particular the fracture-defined *en echelon* structural and topographic patterns exposed in Mt Stirling and Tutakin and Gundaring hills. (WA 1428 Kellerberrin sheet, Run 15, Frame 5238, 16.11.72. Reproduced by permission of DOLA, Perth, Western Australia).

Figure 10. Sketch of part of the southern slopes of Mt Stirling showing protected apron. a: apron, f: fractures into which runoff diverted, w: upper limit of former talus slope and associated subsurface weathering.

Figure 11. General view of Kokerbin Hill from the east, showing dome-on-dome morphology.

Figure 12. Sheet fractures at Kokerbin Hill. Crystals located on opposite sides of the partings are split and demonstrably displaced.

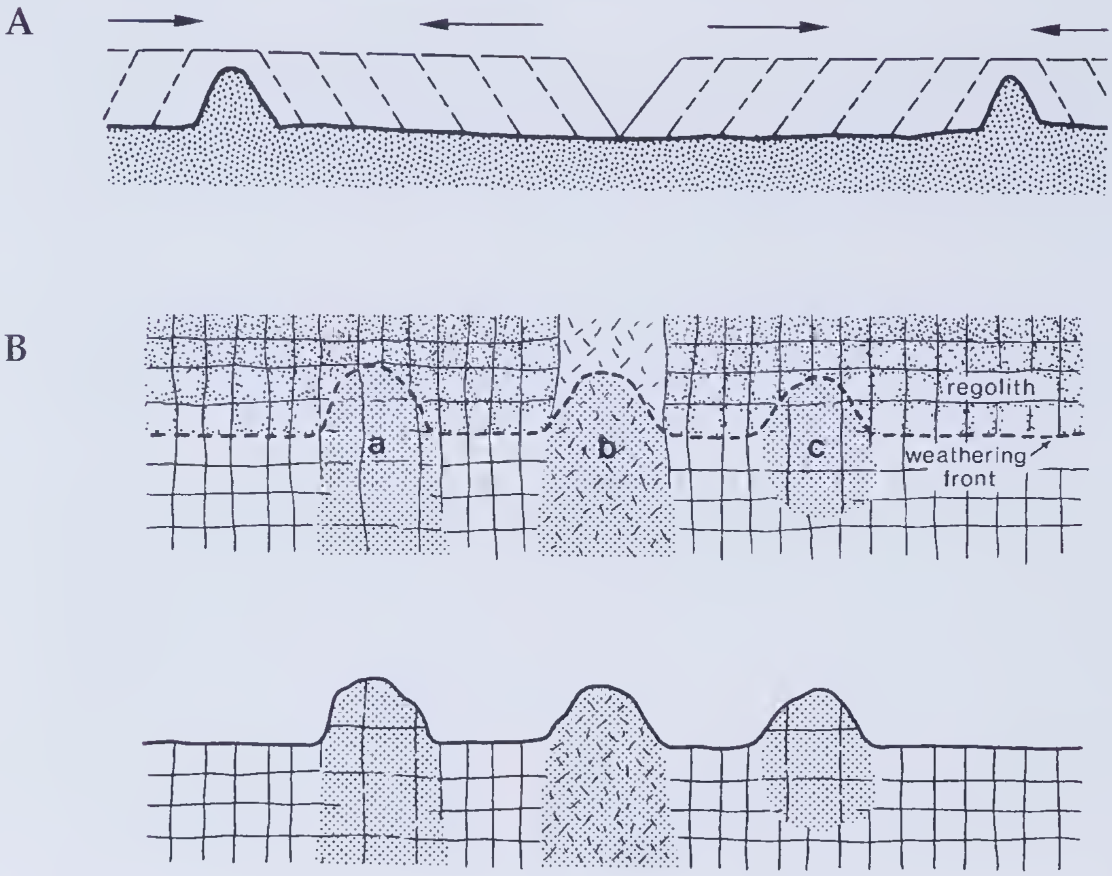

Figure 13. A: Inselbergs/bornhardts due to scarp retreat (modified from King 1942, 1949). B: The two-stage model of inselberg/bornhardt development. a: column of massive rock (few fractures), b: discrete mass of massive rock, c: more resistant rock type. (modified from Falconer 1911)

Another deducible consequence is that in terms of the scarp retreat hypothesis, no residual remnant ought to be older than the duration of a cycle, which, for a large land mass, is of the order of 33 Ma (Schumm 1963; Twidale 1982a). In stratigraphic terms, no bornhardt ought to be older than Oligocene. Many bornhardts (excluding those many exhumed forms) are demonstrably older than this supposed limit. Ayers Rock and The Olgas for instance are of the order of 70 Ma (Twidale 1978; Harris & Twidale 1991) and residuals like The Humps, King Rocks and Jilakin Rock to the southeast of the Salt River Valley, and Ulonging Hill, to the south, are at least of Cretaceous age (Twidale & Bourne 1998).

The age of the Salt River forms can be inferred from their relationship with the lateritised land surface which can in turn be inferred from its relationship with river channels and associated deposits of known age. The weathered (lateritised) land surface of Jutson's (1914) Old Plateau was shaped by rivers graded to these trunk streams. The incision of this drainage system caused the rejuvenation of the tributaries and the stripping of the regolith to expose not only the high plain of Jutson's New Plateau, but also many bornhardts such as Hyden Rock (Twidale & Bourne 1998). Stratigraphic evidence from many palaeochannels in the southern Yilgarn Craton shows that some of the bedrock valleys were incised by the Eocene, for alluvial fills of that age are widely distributed (Commander 1989; Kern & Commander 1993; Clarke 1994; Waterhouse *et al.* 1995) though Miocene and Pliocene fills are also well known (*e.g.* Salama 1997). Presumably incision was not instantaneous along the length of any major river but took considerable time to regress headwards (see also Taylor *et al.* 1985). Given the age of the river rejuvenation it seems likely that it was caused by tectonism related to the separation of the Australian and Antarctic plates, and in particular the uplift and northward tilting of the southern edge of the Yilgarn Craton.

The Salt River Valley is a palaeochannel of at least Miocene age (Salama 1997; Fig 14). A river has probably occupied the present sector since the Early Tertiary. Uplift of the Darling Range blocked the previous drainage, and caused the formation of a shallow lake but rejuvenation and regression of the Avon has drained the lake (of which only minor remnants remain) and revived the Salt River system, so that the palaeochannel cut some 70 m into the granitic country rock before being infilled to its present level. Thus the local evidence derived from the demonstrated minimum age of the river channel points to river incision prior to the Miocene. It was in this phase of incision that tributaries to the Salt River were regraded and the divides to either side of the channel dissected. It was then that Mt Stirling and the other bornhardts were exposed. This is a minimum age, for the regional evidence suggests an Early, rather than a Middle,

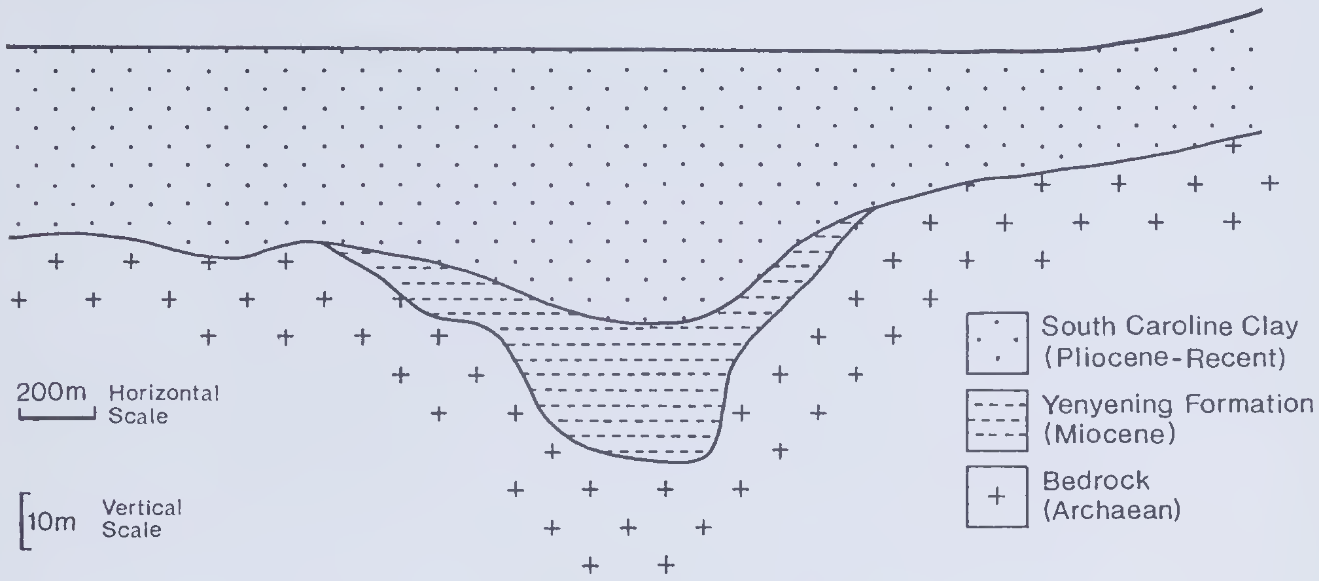

Figure 14. Section through the Salt River showing buried basement channel and fills. The Yenyening Formation consists of clay, sand and lignite (simplified from Salama 1997)

Tertiary age for the drainage system and this part of the Salt River Valley may have been eroded much earlier in the Tertiary, but alluviated during the Miocene.

Other explanations for bornhardt formation which are, *prima facie*, relevant include the suggestion that bornhardts may be developed on intrusive stocks which are, implicitly, different and more resistant (composition, texture, fracture density) than the host masses. In the Salt River Valley there is no evidence that the rocks in which the bornhardts are shaped are compositionally or texturally different from plains rocks, though there are compositional and textural variations within many of the bornhardts.

Mt Stirling, Gundaring Hill, Tutakin Hill, Kokerbin Hill and Mt Caroline are domes, the bevelled crests and shoulders of which originated as a result of weathering in the zone of fluctuating water table in Cretaceous times (Fig 15). The ancestral massive compartment that was to become Nangeen Hill was entirely below the surface and its outer layers were reduced to regolith, and blocks and boulders within the regolith, so that on exposure it appeared as a nubbin. Middle Dome was similarly wholly hidden beneath the regolith and its concentric outer sectors, or shells, were so weathered that soon after exposure they were eliminated to leave the hemispherical core as a rounded hill.

On Mt Stirling, Tutakin Hill and Mt Caroline there are small protuberances or knolls standing higher than the crestal bevel or shoulder. Given their present elevations, those of the adjacent watersheds and the known local thickness of the lateritic regolith, they were most likely exposed above the laterite surface. Alternatively, if the regolith thickened in the valley, or present elevations are misleading due to tilting, they may have been irregularities projecting into the base of the regolith (Fig 14). On Kokerbin Hill, the shoulder or break of slope between the two domes probably denotes the level of the regolith and the higher or summit dome may well have been a low hill projecting above the lateritised land surface in later Cretaceous-early Eocene times. Certainly the higher dome (above the level of the car park) is intensely weathered, with many shelters and tafoni developed beneath large residual boulders and sheet structures (Fig 6A,B).

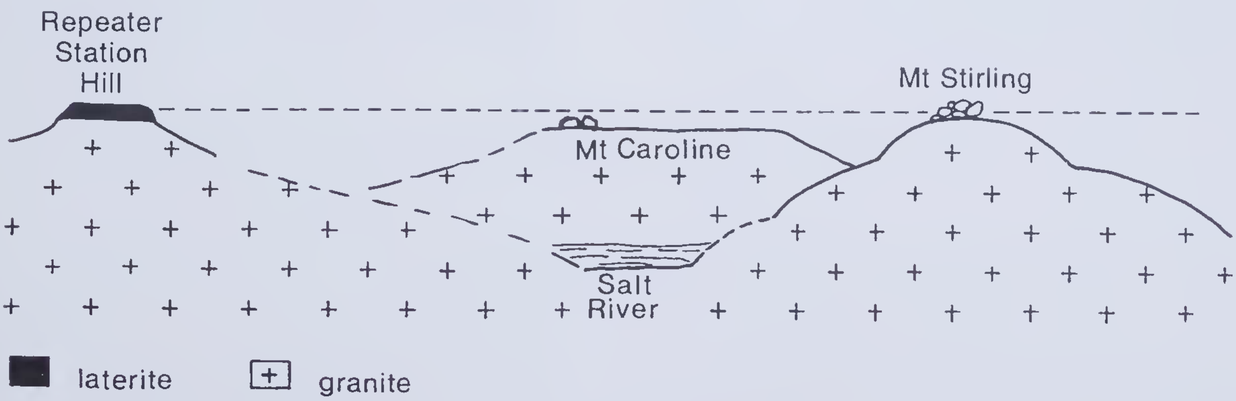

Figure 15. Diagrammatic section of the Salt River Valley showing location of residuals in relation to weathering surface.

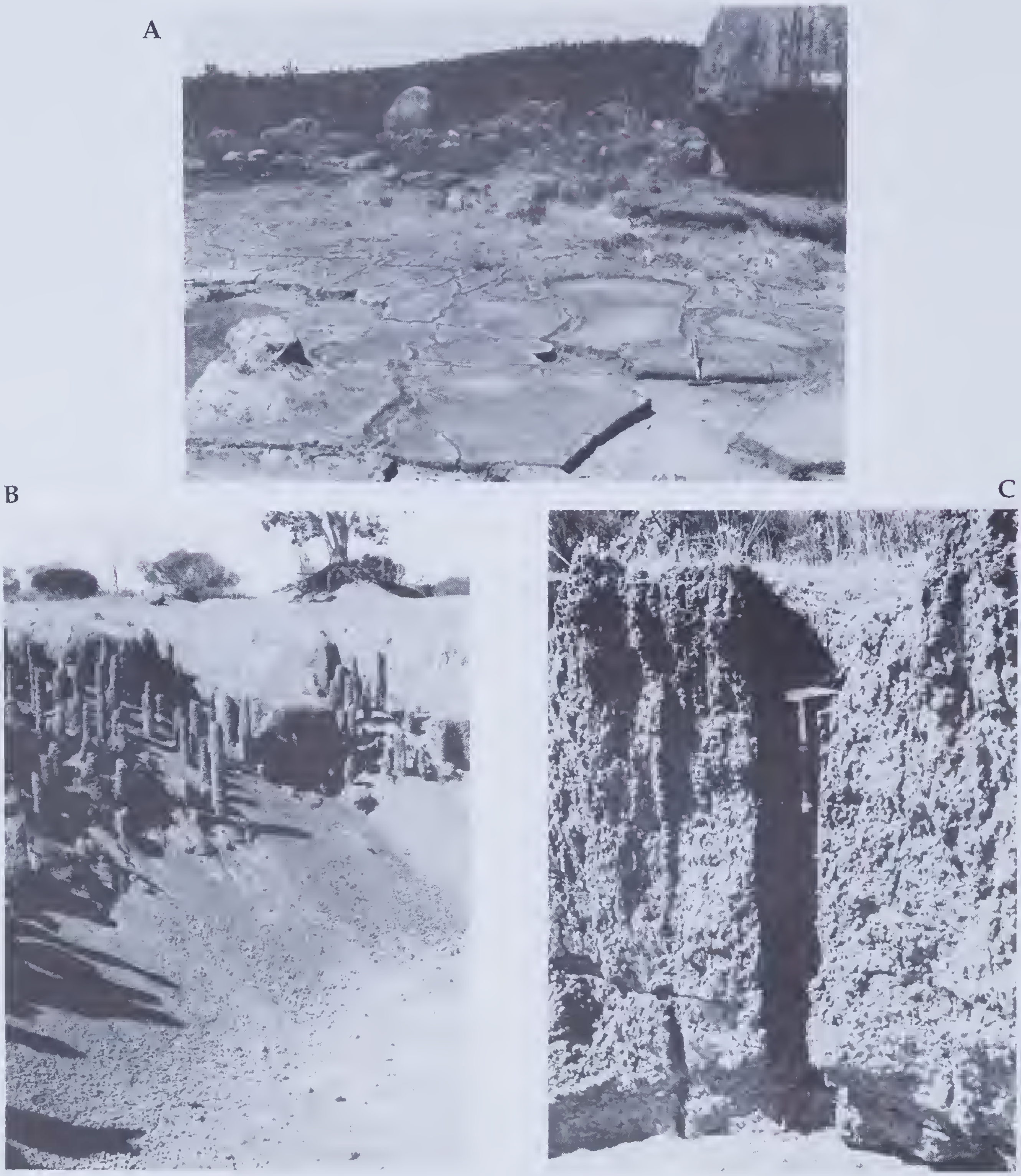

Figure 16. A: Tesselated pavement at Boulder Rock. B: Two metre high pinnacles of pisolitic iron oxide cemented by kaolinite near Ulonging H S. C: Pipes in pisolitic zone of laterite at Repeater Hill.

Thus the Salt River Valley residuals are typical two-stage forms, with two major ages. The first relates to the period in the Cretaceous (and possibly also in earlier Mesozoic times, including the Triassic and Jurassic) when they were prepared by differential moisture weathering in the subsurface, which exploited varied fracture densities in the bedrock. The second pertains to the period of exposure resulting from the incision of the Salt River and its tributaries. There is, however, the possibility that minor precursors of several of the present forms were already standing in relief above the lateritised land surface in the Cretaceous. In this they are analagous to various other very old residuals of the region, bornhardts such as The Humps, King Rocks, Jilakin Rock and the upper dome of Boyagin Rock (Twidale & Bourne 1998).

Iron Impregnation and Tesselated Pavement

If, as is suggested, the bornhardts of the Salt River Valley evolved beneath a lateritised weathered land surface, *i.e.* one in which iron oxides such as haematite and goethite were concentrated in the B-horizon, then it is strange that ferruginous staining and associated effects are not more prominent on the bornhardts. At Boulder Rock, in the Darling Ranges, about 20 km east of Kelmscott, however, iron staining of the surface is preserved and a tesselated pavement in granite (Fig 16A) is also developed. Iron oxides have evidently percolated down vertical fractures and indurated the adjacent parts of each small slab, leading to the formation of raised rims enclosing a shallow depression in each component of the pavement. Some iron salts, however, have been contributed in dust blown to the site by easterly winds (Glassford & Semeniuk 1990; Brimhall *et al.* 1991).

Similarly tesselated granite surfaces have been observed on the lower slopes of Domboshawa, a bornhardt located a few kilometres northeast of Harare, in Zimbabwe. There the patterns clearly developed at the weathering front, beneath a thin regolith carrying a cover of mosses and small shrubs.

Eucalypts spread over the Australian continent and became dominant beginning in the Miocene. Waters containing polyphenols, which are produced by eucalypt litter, are especially effective in dissolving iron-rich materials (see Bloomfield 1957), so that there has been ample time for iron oxides to be translocated from lateritic profiles into the deeper regolith and to the weathering front. However Boulder Rock has, in geological terms, and in comparison with the Salt River residuals (and others in the southern Yilgarn), only recently been exposed; remnants of the deeply weathered land surface occur extensively in the Darling Ranges and in its eastern dissected margin. Perhaps there has not yet been time for the ferruginous minerals precipitated at and near the weathering front to be leached from the system by meteoric waters. To the east, on the other hand, remnants like those in the Salt River Valley have been longer exposed to the elements so that despite the lower average precipitation there has been more opportunity to wash away iron concentrations, except at minor, exceptional sites, such as iron oxide-capped spikes on the eastern dome of Hyden Rock. In addition, alkaline groundwaters and runoff may here, as elsewhere, be especially effective solutional (weathering) agents.

Pisolitic Pinnacles

The piped structure of the ferruginous carapace exposed at Repeater Hill is germane to the origin of pinnacles of pisolitic zone laterite (Fig 16B,C) developed near Ulonging H S (Althorpe Peaks), some 18 km ESE of Quairading and 30 km SSW of the Salt Creek area. The pinnacles are exposed in a borrow pit and rise about 2 m from a debris slope composed of disintegrated pisolitic detritus. They are cemented by kaolinite and stand about a metre below the level of the original laterite surface preserved, for example, around trees. Circular patterns with white and red clay filling interstices in the adjacent floor of the pit suggest that pinnacle structures were formerly (before quarrying) more extensive. Moreover the occurrence of round patches of white clay with pisolites shows that associated structures extend an unknown distance in depth, below the floor of the quarry. They could have originated as infillings of pipes such as those exposed at Repeater Hill, where the A-horizon, which is composed overwhelmingly of quartz, nevertheless contains minor amounts of kaolinite, feldspar and chlorite. Thus the Ulonging pinnacles are pipe fills of detrital pisolites cemented by clay. They occur in a pisolitic zone and stand lower than the original surface and sandy A-horizon. They are not, however, due to solution but to flushing of fines and partial infilling by clay (Twidale & Milnes 1983; Glassford 1987; Herwitz & Muhs 1995).

Conclusions

The area south of Kellerberrin includes, first, remnants of the weathered (lateritised) land surface that is widely preserved in the southern Yilgarn Craton, and the age of which can be deduced; second, a sector of the Salt River Valley the origin and age of which has been determined; and third, several prominent granitic bornhardts. This assemblage of landforms allows the origin and age of the bornhardts to be suggested.

The bornhardts are multi-stage forms due to differential weathering along fracture sets and systems initiated more than two billion years earlier. They were prepared by subsurface weathering during the Cretaceous, and possibly earlier Mesozoic times, and exposed as landforms during the Tertiary, certainly during the Miocene, although probably from the Eocene onwards. The crestal domes and minor nubbins present on the higher residuals may have stood above the lateritised landscape and be similar in age to several other of the older Yilgarn bornhardts. The lateritic carapace has affected minor landform development at Boulder Rock, and piping in the duricrust has resulted in pinnacles in the piedmont of Althorpe Peaks.

Acknowledgements: The writers thank two referees for constructive comments and Mr & Mrs R Mouritz of Hyden for facilitating the field work on which the paper is based.

References

Anhaeusser C R 1984 Structural elements of Archaean granite-greenstone terranes as exemplified by the Barberton Mountain Land, southern Africa. In: Precambrian Tectonics Illustrated (eds A Kröner & R Greiling). Schweitzerbart'sche, Stuttgart, 57-78.

Anon. 1975 The Geology of Western Australia. Geological Survey of Western Australia, Perth, Western Australia. Memoir 2.

Bornhardt W 1900 Zur Oberflächengestaltung und Geologie Deutsch Ostafrikas. Reimer, Berlin.

Bloomfield C 1957 The possible significance of polyphenols in soil formation. Journal of the Science of Food and Agriculture 8:389-392.

Brimhall G H, Lewis C J, Ford C, Bratt J, Taylor G & Warin O 1991 Quantitative geochemical approach to pedogenesis: importance of parent material reduction, volumetric expansion, and eolian influx in lateritization. Geoderma 51:51-91.

Campbell E M 1997 Granite landforms. Journal of the Royal Society of Western Australia 80:101-112.

Chin R J 1986 Corrigin, Western Australia, map sheet SI 50-3 International Index. 1:250,000 Geological Series - Explanatory Notes. Geological Survey of Western Australia, Perth, Western Australia.

Clarke J D A 1994 Geomorphology of the Kambalda region, Western Australia. Australian Journal of Earth Sciences 41:229-239.

Commander D P (compiler) 1989 Hydrogeological Map of Western Australia. Scale 1:2,500,000. Geological Survey of Western Australia, Perth, Western Australia.

Cotton C A 1948 Landscape. Whitcombe & Tombs, Christchurch.

Falconer J D 1911 Geology and Geography of Northern Nigeria. Macmillan, London.

Glassford D K 1987 Cainozoic stratigraphy of the Yeelirrie area, northeastern Yilgarn Block, Western Australia. Journal of the Royal Society of Western Australia 70:1-24.

Glassford D K & Semeniuk V 1990 Stratification and disconformities in yellow sands of the Bassendean and Spearwood Dunes, Swan Coastal Plain, South-western Australia. Journal of the Royal Society of Western Australia 72:75-93.

Godard A 1977 Pays et Paysages du Granite. Presses Universitaires de France, Paris.

Harris W K & Twidale C R 1991 Revised age for Ayers Rock and The Olgas. Transactions of the Royal Society of South Australia 115:109.

Herwitz S R & Muhs D R 1995 Bermuda solution pipe soils: a geochemical evaluation of eolian parent materials. In: Terrestrial and Shallow Marine Geology of the Bahamas and Bermuda (eds H A Curran & B White), Geological Society of America Boulder, Colorado. Special Paper 300:311-323.

Hickman A H 1984 Archaean diapirism in the Pilbara Block, Western Australia. In: Precambrian Tectonics Illustrated (eds A Kröner & R Greiling). Schweitzerbart'sche, Stuttgart, 113-127.

Hills E S 1940 Physiography of Victoria: An Introduction to Geomorphology. Whitcombe & Tombs, Melbourne.

Holmes A 1918 The Pre-Cambrian and associated rocks of the District of Mozambique. Quarterly Journal of the Geological Society of London 74:31-97.

Jutson J T 1914 An outline of the physiographical geology (physiography) of Western Australia. Geological Survey of Western Australia, Perth, Western Australia. Bulletin 61.

Kemp E M 1978 Tertiary climatic evolution and vegetation history in the Southeast Indian Ocean region. Palaeogeography Palaeoclimatology Palaeoecology 24:169-208

Kern A M & Commander D P 1993 Cainozoic stratigraphy in the Roe Palaeodrainage of the Kalgoorlie region, Western Australia. Geological Survey of Western Australia, Perth, Western Australia. Report (Professional Papers) 34:85-95.

King L C 1942 South African Scenery. Oliver & Boyd, Edinburgh.

King L C 1949 A theory of bornhardts. Geographical Journal 112:83-87.

Lamego A R 1938 Escarpas do Rio de Janeiro. Departamento Nacional da Produçao Mineral (Brasil). Servicio Geologico e Miniero, Rio De Janiero, Brasil. Boletim 93.

Linton D L 1952 The significance of tors in glaciated lands. Proceedings of the International Geographical Union 8th General Assembly, 17th International Congress: 354-357.

Linton D L 1955 The problem of tors. Geographical Journal 121:470-487.

Mabbutt J A 1952 A study of granite relief from South West Africa. Geological Magazine 89:87-96.

Mabbutt J A 1961 "Basal surface" or "weathering front"? Proceedings of the Geologists' Association of London 72:357-358.

MacGregor A M 1951 Some milestones in the Precambrian of Rhodesia. Transactions of the Geological Society of South Africa 54:27-71.

Main B Y 1997 Granite outcrops: a collective ecosystem. Journal of the Royal Society of Western Australia 80:113-122.

Muhling P C & Thom R 1979 Corrigin, Western Australia, map sheet SI/50-3 International Index. 1:250,000 Geological Series. Geological Survey of Western Australia, Perth, Western Australia.

Myers, J S 1993 Precambrian history of the West Australian Craton and adjacent orogens. Annual Reviews of Earth and Planetary Science 21:453-485.

Myers J S & Watkins K P 1985 Origin of granite-greenstone patterns, Yilgarn Block, Western Australia. Geology 13:778-780.

Nemchin A A, Pidgeon R T & Wilde S A 1994 Timing of the late Archaean granulite facies metamorphism and the evolution of the southwestern Yilgarn Craton of Western Australia - evidence from U-Pb ages of zircons from mafic granulites. Precambrian Research 68:307-321.

Ollier C D 1960 The inselbergs of Uganda. Zeitschrift für Geomorphologie 4:43-52.

Ollier C D & Tuddenham W G 1962 Inselbergs of central Australia. Zeitschrift für Geomorphologie 5:257-276.

Palfreyman W D 1984 Guide to the Geology of Australia. Bureau of Mineral Resources, Canberra. Bulletin 181.

Salama R B 1997 Geomorphology, geology and palaeohydrology of the broad alluvial valleys of the Salt River System, Western Australia. Australian Journal of Earth Sciences 44:751-765

Schumm S A 1963 Disparity between present rates of denudation and orogeny. United States Geological Survey, Washington D.C. Professional Paper 454.

Selby M J 1977 Bornhardts of the Namib Desert. Zeitschrift für Geomorphologie 21:1-13.

Taylor G, Taylor G R, Bink M, Foudoulis C, Gordon I, Hestrom J, Minello J & Whippy F 1985 Pre-basaltic topography of the northern Monaro and its implications. Australian Journal of Earth Sciences 32:65-71.

Thomas M F 1965 Some aspects of the geomorphology of domes and tors in Nigeria. Zeitschrift für Geomorphologie 9:63-81.

Thomas M F 1966 The origin of bornhardts. Zeitschrift für Geomorphologie 10:478-480.

Twidale C R 1964 A contribution to the general theory of domed inselbergs. Conclusions derived from observations in South Australia. Transactions and Papers of the Institute of British Geographers 34:91-113.

Twidale C R 1978 On the origin of Ayers Rock, central Australia. Zeitschrift für Geomorphologie SupplementBand 31:177-206.

Twidale C R 1980 The origin of bornhardts. Journal of the Geological Society of Australia 27:195-208.

Twidale C R 1981 Granitic inselbergs: domed, block-strewn and castellated. Geographical Journal 147:54-71.

Twidale C R 1982a Granite Landforms. Elsevier, Amsterdam.

Twidale C R 1882b The evolution of bornhardts. American Scientist 70:268-276.

Twidale C R & Bourne J A 1975 Episodic exposure of inselbergs. Geological Society of America Bulletin 86:1473-1481.

Twidale C R & Bourne J A 1998 Origin and age of bornhardts, southwest of Western Australia. Australian Journal of Earth Sciences. In press.

Twidale C R & Campbell E M 1984 Murphy Haystacks, Eyre Peninsula, South Australia. Transactions of the Royal Society of South Australia 108:175-183.

Twidale C R & Milnes A R 1983 Slope processes active late in arid scarp retreat. Zeitschrift für Geomorphologie 27:343-361.

Twidale C R & Sved G 1978 Minor granite landforms associated with the release of compressive stress. Australian Geographical Studies 16:161-174.

Twidale C R & Vidal Romani J R 1994 The Pangaean inheritance. Cuadernos Laboratorio Xeolóxico de Laxe 19:7-36.

Vidal Romani J R & Twidale C R 1998 Formas y Paisajes Graniticos. Servicio de Publicacións da Universidade da Coruña, A Coruña. Serie Monografías 55.

Vidal Romani J R, Twidale C R, Campbell E M & Centeno J de D 1995 Pruebas morfológicas y estructurales sobre el origen de las fracturas de descamación. Cadernos Laboratorio Xeolóxico de Laxe 20:307-346.

Vidal Romani J R, Twidale C R, Bourne J & Campbell E M 1998. Espeleotemas y formas constructivas en granitoides. In: Investigaciones recientes de la Geomorfologia española (eds A Gomez Ortiz & F Salvador Franch), Servei de Gestio i Evolucio del Paisatge (Universitat de Barcelona)/ Sociedad Española de Geomorfologia/ Universidad de Granada, Barcelona, 777-782.

Wallach J L, Mohajer A A, McFall G H, Bowlby J R, Pearce M & McKay D A 1993 Pop-ups as indicators of seismic hazard in intraplate eastern North America. Quaternary Proceedings. Neotectonic Recent Advances 3:67-83.

Waterhouse J D, Commander D P, Prangley C & Backhouse J 1995 Newly recognised Eocene sediments in the Beaufort River palaeochannel. Geological Survey of Western Australia, Perth, Western Australia. 1993-94 Annual Review 82-86.

Wilhelmy H 1958 Klimamorphologie der Massengesteine. Westermann, Braunschweig.

Williams G 1936 The geomorphology of Stewart Island, New Zealand. Geographical Journal 87:238-337.

Willis B 1934 Inselbergs. Annals of the Association of American Geographers 24:123-129.